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TELLUS

Age and renewal time of water masses in a semi-enclosed basin – application to the Gulf of Finland

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ABSTRACT

To estimate the water-renewal time of the Gulf of Finland, a numerical-model simulation comprising the years 1987–1992 was carried out for realistic meteorological forcing. The results concerning water age as well as renewal index proved to reflect properties of the mean circulation system. The highest water ages (of around 2 yr) were found in the south-eastern part of the Gulf. The water-age distribution after the 5-yr simulation proved to be almost identical to that obtained after 3 yr, indicating that the circulation in the Gulf may be rather stable. The analysis of the renewal-index results showed that it takes around 5 yr to renew 98% of the water masses of the Gulf. When local maxima of the renewal index are found in conjunction with high water ages, this may indicate that the region is particularly vulnerable to eutrophication.

1. Introduction

An analysis of the state variables is not always the best way to investigate the hydrography of a water body, particularly so when long-term phenomena are to be examined. As will be shown, ordinary budget considerations (Knudsen, 1900) may not provide much relevant information concerning water-renewal rates in semi-enclosed basins, because these estimates do not directly reflect the internal dynamics of the basin. Furthermore, the results of such calculations depend strongly on the method employed. For determining these rates an auxiliary variable denoted 'water age', first suggested by Bolin and Rodhe (1973), proves to be helpful. To complement the information derived from water-age analysis and to estimate the renewal time in the basin under consideration, as well as the location of its weakly ventilated areas, in what follows we introduce another passive tracer, namely the renewal index. This quantity describes the evolution of the amount of 'original water' remaining in each location of the basin. Both of these auxiliary variables are described by an advection-diffusion equation and are easily included in a three-dimensional hydrodynamic model. The aim here is to demonstrate how an analysis of these quantities can be used for estimating the rate of water renewal characterizing a semi-enclosed basin.

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The present study will be focused on the Gulf of Finland, located in the north-eastern part of the Baltic (Fig. 1). It is an elongated estuary, with a mean depth of 37 m (maximum depth 123 m) and a volume of 1103 km^3, i.e. around 5% of the total volume of the Baltic Sea. A pronounced longitudinal salinity gradient is present, because the western part of the Gulf is a direct continuation of the Baltic Sea proper, whereas the eastern end receives the largest single freshwater inflow to the Baltic Sea, namely the River Neva. The stratification is furthermore highly variable in both space and time, where the large seasonal variability of the incoming solar radiation plays a considerable role (cf. Alenius et al., 1998).

The equations for the water age and the renewal index will be 'piggy-backed' on a three-dimensional numerical ocean model (Andrejev and Sokolov, 1989; Andrejev et al., 2004; Myrberg and Andrejev, 2003). The calculations will be carried out for the period 1987–1992, chosen because, as to be further discussed in Section 5, the entire water mass of the Gulf is renewed during a period of this length. This suite of years furthermore did not include any major inflows of saline water to the Baltic Sea, and thus no exceptional changes of the stratification were to be expected.

Following Witting (1912) and Palmén (1930), our main focus will be on studying the biologically active near-surface layers. In Section 2 we describe the implementation of the circulation model as well as the data sets and forcing functions employed for the numerical experiments. In the following section we discuss the mean circulation and the related water exchange in the Gulf

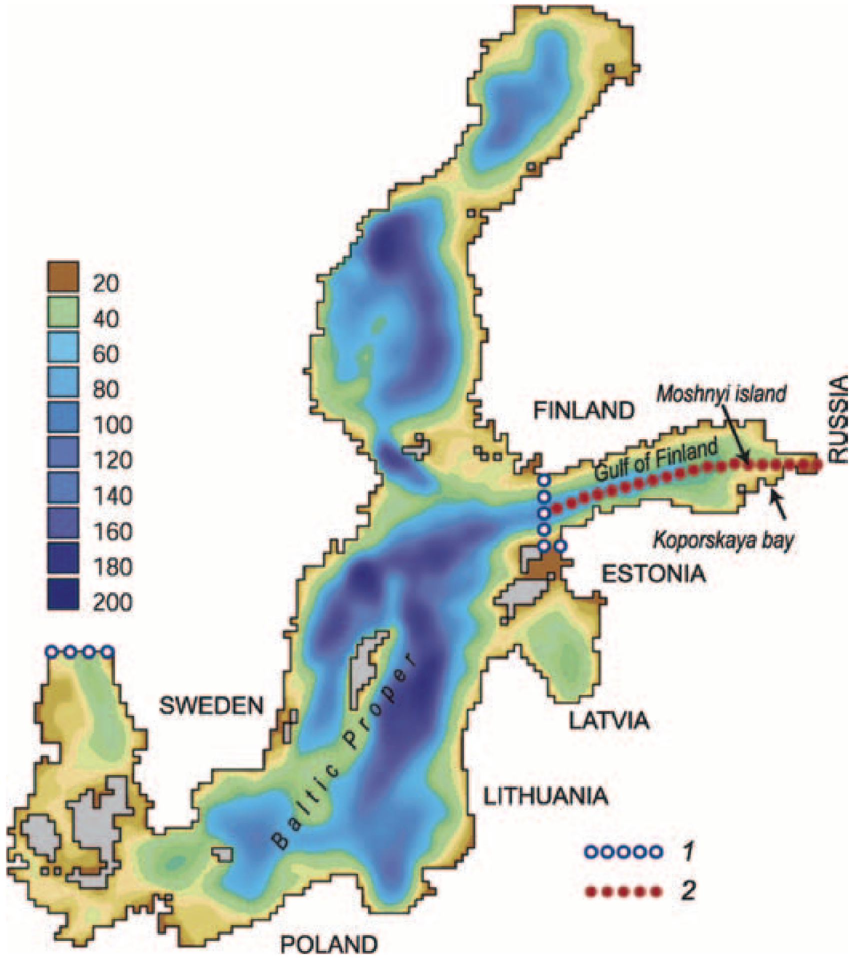

Fig 1. The bottom topography of the Baltic Sea reproduced from Stigebrandt and Wulff (1987) and relevant geographical locations. The open boundaries are marked with white dots (denoted as 1) and the section used in the analysis of the model results in the Gulf of Finland is marked with red dots (denoted as 2).

of Finland, whereafter in Section 4 we introduce the auxiliary variables for estimating the water-renewal rate. In Section 5 we discuss the overall results of the investigation in considerable detail, and hereafter the study is concluded by a summary as well as a review of some practical consequences of the investigation, possibly to be kept in mind when taking environmental action.

2. The model

The numerical model to be employed (Andrejev and Sokolov, 1989; Andrejev et al., 2002, 2003; Engqvist and Andrejev, 2003; Myrberg and Andrejev, 2003) is of the time-dependent, free-surface, baroclinic, three-dimensional Boussinesq variety. Simplifications in the form of the hydrostatic approximation, the incompressibility condition, a Laplacian closure hypothesis for subgrid-scale turbulent mixing, and the traditional f-plane approximation are made.

The modelling is based on a 'nested-grid' system, where the large-scale Baltic model is run using a coarse grid and its output is used as open-boundary data for the local highly-resolving version of the model which is applied to the Gulf of Finland. At the boundary between the grids a linear interpolation of the coarse-grid results is carried out to provide data for the high-resolution model. Based on the grid sizes, the horizontal kinematic eddy diffusivity coefficient μ is prescribed to be constant at 50 m^2 s^{-1} for the Baltic Sea proper and 30 m^2 s^{-1} for the Gulf of Finland. The vertical eddy diffusivity coefficient ϑ is taken to be dependent on the local velocity shear and buoyancy forces using the Kochergin (1987) parameterization based on the reduced turbulent kinetic energy (TKE) equation.

Quadratic laws govern the wind and bottom stress (Bunker, 1977; Niiler and Kraus, 1977). The heat transfer and the radiative balance at the air–sea interface are calculated following Lane and Prandle (1996). For salinity, the corresponding flux is to a lowest-order approximation prescribed as zero, because the difference between precipitation and evaporation (although minute for the Gulf of Finland) is not known accurately due to a lack of observations (see, for example, Omstedt et al., 1997, 2000).

The winters during the period of interest were rather mild and hence the Gulf was mostly free of ice, hereby permitting a highly simplifed parameterization of ice formation and destruction.

Although no ice-drift is modelled, certain effects of sea ice are taken into account because for water temperatures below -0.2°C, the wind stress is decreased, and at 0.0 °C the heat flux through the ice ceases as long as cooling conditions prevail.

For the open boundary of the large-scale Baltic model, a passive radiation condition is used as regards the surface elevation (Orlanski, 1976; Mutzke, 1998), whereas a combination of an active radiation condition with a sponge-layer technique is used for the other variables. Vertical convection is parametrized using a standard heuristic algorithm (Andrejev et al., 2003).

Data assimilation was carried out for the coarse-resolution Baltic Sea model because, throughout the experiment, the salinity and temperature fields were slightly corrected each July using the Stauffeur and Bao (1993) procedure. This nudging was only implemented for the coarse-resolution Baltic model, because the sole purpose of this model was to generate an open-boundary condition for the highly resolving model of the Gulf of Finland.

2.1. *Set-up of the numerical model experiments*

The 5-yr period from 1 August 1987 to 31 August 1992 was investigated using the model, where the spin-up of the model was accomplished during the period 1–31 July 1987. The open boundary of the large-scale model domain is located in the Kattegatt along latitude 57°35′N. Previous investigations (Andrejev et al., 2003) indicate that the coarse-resolution model yields an adequate open-boundary condition for the Gulf model. The open boundary of this smaller domain is constituted by two parts: the western one coinciding with longitude 22°32′E and the southern with latitude 59°05′N. Both models have the same vertical resolution, but the horizontal resolutions are 5 and 1 nautical miles, respectively. A linear interpolation scheme is used at the boundaries between the grids with different resolutions. The time-steps used were 2 h for the Baltic Sea model and 0.5 h for the Gulf of Finland model. The standard bathymetry provided by Seifert and Kayser (1995) was used. The large-scale Baltic model comprises 18 levels in the vertical with a monotonically increasing layer thickness towards the bottom, whereof the three deepest layers are absent in the model for the shallow Gulf of Finland.

We have used Swedish Meteorological and Hydrological Institute (SMHI) standard gridded meteorological data for 1987–1992 with a spatial resolution of 1° for the entire Baltic Sea area and a temporal resolution of 3 h. Because the wind velocities in the data set represent geostrophic values, they must be extrapolated to the sea surface. A standard method for this correction is to multiply the wind speed by a factor of 0.6 and deflect the direction 15° counterclockwise (Bumke et al., 1998). The monthly mean values of river discharges for 1970–1990 (Bergström and and Carlsson, 1994; Sokolov et al., 1997) were used.

The initial temperature and salinity fields for both the Baltic Sea and Gulf of Finland model versions were assembled using a data assimilation system due to Sokolov et al. (1997), which in turn is coupled to a Baltic environmental data base (Wulff and Rahm, 1991) and to the three-dimensional model employed here. The initial fields for August 1987 were assembled using temperature and salinity data from all months of July from 1980 to 1992 (during which period no significant saltwater intrusions to the Baltic took place) due to a dearth of observational field data from July 1987. The model run was initiated from a quiescent state.

3. Mean circulation and water exchange

A number of estimates of the mean circulation and time-scale of the water-exchange processes in the Gulf of Finland have previously been established; see, for example, Witting (1912) and Palmén (1930). These results were based on rather sparse field measurements, which is why it deserves mention that present-day modelling tools permit us to study these properties of the Gulf in considerably greater detail. Estimates of the annual water exchange have been presented by, for example, Witting (1912), who calculated inflow and outflow of 480 and 600 $km^3\ a^{-1}$, respectively (corresponding to mean entrance-region velocities of approximately 1 cm s^{-1}). This appears to be an underestimate when compared not only to the modelling results by Andrejev et al. (2004), but also to recent observations reported by Sarkkula (1991) as well as Mikhailov and Chernyshova (1997). A discrepancy of this magnitude is, however, not surprising, because Witting's calculations were based on straightforward budget estimates using the classical Knudsen formula (Knudsen, 1900). The input of river water to the Gulf is around 115 $km^3\ a^{-1}$ (Bergström and Carlsson, 1994), and thus the difference between inflow and outflow is expected to be roughly 110–120 $km^3\ a^{-1}$. Using a three-dimensional numerical model, Lehmann and Hinrichsen (2000) obtained differences of 148 and 103 $km^3\ a^{-1}$ from simulations over the years 1988 and 1994, respectively.

In a recent study of the Gulf of Finland by Andrejev et al. (2004) an investigation of the mean circulation, its persistency (defined for currents as the ratio between their vector and scalar mean speed; cf. Palmén, 1930) and the water exchange between the Gulf and the Baltic proper was carried out using the three-dimensional model to be employed also in this study. According to Andrejev et al. (2004) the circulation of the uppermost model layer (0–2.5 m) is mainly wind-driven, with typical velocities of 5–10 cm s^{-1}. The mean circulation below the immediate surface layer and down to 45 m (Fig. 2) is dominated by a cyclonic circulation system encompassing nearly the entire Gulf (whereas in the easternmost part the circulation is forced by the water masses debouching from the River Neva). The outflowing part of this cyclonic circulation system (namely, westward-directed flow), located slightly north of the longitudinal axis of the Gulf, is characterized by a persistency of 50–60% (Fig. 3). On the southern side of this outflow meso-scale eddies are found, a feature which also is encountered at the entrance area of the Gulf. In this latter region, a high persistency (50–80%) proved to characterize the inflowing waters on the southern side of the

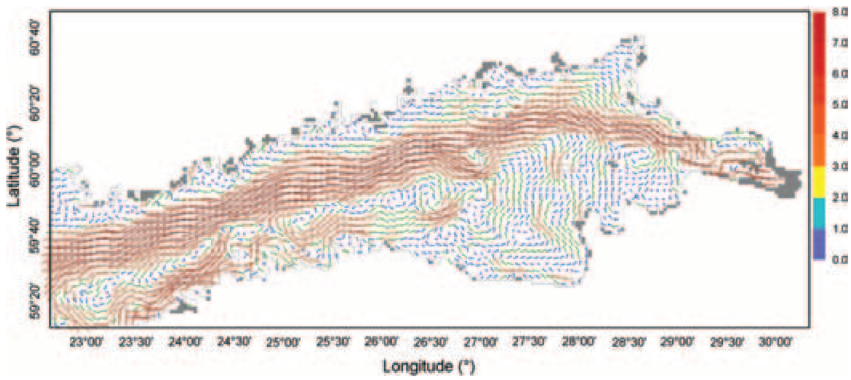

Fig 2. The simulated mean circulation in the subsurface layer between 2.5 and 7.5 m from 31 August 1987 to 31 August 31 1992. Only results from every second grid point are shown.

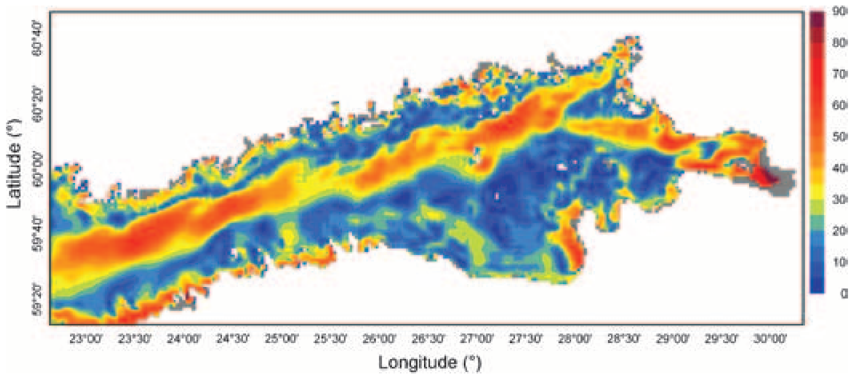

Fig 3. The simulated 5-yr mean persistency in the subsurface layer between 2.5 and 7.5 m.

Gulf as well as the outflow north of the longitudinal axis. As expected, the River Neva inflow has a persistency of more than 90%. The figure furthermore shows that in the deeper parts of the Gulf the effects of bottom topography manifest themselves in the form of persistent small-scale vortices. Here it may finally also be noted that there are regions in the eastern part of the central Gulf with persistencies exceeding 50% over the entire water column, indicating the presence of quasi-stationary areas where a smaller-scale internal circulation dominates. It is worth emphasizing that some of these general persistency results have been confirmed by observations (Sarkkula, 1991; Mikhailov and Chernyshova, 1997) as well as by independent numerical-model results (Lehmann et al., 2002; Stipa, 2004).

The numerical values characterizing the water exchange prove to be highly dependent on the location of the cross-section where this exchange is assumed to take place. The mean circulation pattern, as shown in Fig. 2, indicates the presence of a meso-scale cyclonic circulation system at the entrance to the Gulf. Hence water masses may 'visit' the Gulf for brief periods without affecting the general hydrography of the central and eastern parts. The water-exchange estimates are furthermore dependent on the methods employed for the analysis of the model results. Two different approaches were pursued in the study due to Andrejev et al. (2003). *Pro primo*, the inflow and outflow were summed over the transect between Hanko and Osmussaar (assumed to constitute the western border of the Gulf) for each time-step (30 min) of the 5-yr simulation, a procedure which yielded average flows for the period 1987–1992. These calculations, taking into account all water masses transgressing the section, yielded average inflow and outflow of 3154 and 3273 km^3 a^{-1}, respectively. *Pro secundo*, the water exchange across the section was estimated on the basis of the average velocities for the 5-yr simulation period (corresponding to the mean circulation fields). Using this latter method, the short-term variability of the circulation will be filtered out, whereas the quasi-stationary cyclonic meso-scale circulation pattern at the western end of the Gulf still is taken into account. This estimate yielded an inflow of 1417 km^3 a^{-1} and an outflow of 1532 km^3 a^{-1}. The difference between inflow and outflow was thus 119 and 115 km^3 a^{-1} when the first and second techniques, respectively, were used; both values reasonably close to the total river runoff debouching into the Gulf. Summarizing these results, we can conclude that direct estimates of the water exchange can only infrequently be used in practice because of their uncertainty. Hence, these numbers cannot answer the questions of to what extent the inflowing water affects the inner part of the Gulf, or how far eastwards this water penetrates. As will be seen, considerably more information regarding these matters can be obtained by carrying through an analysis of the water age and renewal index.

4. Definition of the water age and renewal index

The concept of water age was originally introduced by Bolin and Rodhe (1973), and subsequently a large number of investigations focusing on this topic have been published. Comprehensive reviews of these studies as well as the theory itself can be found in Delhez et al. (1999) and in Deleersnijder et al. (2001). The general theory of water age Deleersnijder et al. (2001) regards the seawater as a mixture of several constituents, namely, pure water, dissolved salts, pollutants, plankton, etc. Following Delhez et al. (1999), the age of a 'particle' of a seawater constituent is regarded as 'the time elapsed since the particle under consideration left the region in which its age is prescribed to be zero'. Deleersnijder et al. (2001) apply the Eulerian age theory, within which advection, diffusion, production and destruction of seawater constituents are properly accounted for and an equation is established for a concentration-distribution function (i.e. the dimensionless mass fraction at a given time and location), whereafter the equation for the age concentration can be derived. Taking into account that the major constituent of seawater is pure water, which is neither produced nor destroyed, the problem of seawater age may thus to a high degree of accuracy be reduced to an advection-diffusion equation governing the evolution of the water-age concentration (Deleersnijder et al., 2001). This approximation was successfully used by, for example, Thiele and Sarmiento (1990), England (1995) and Engqvist (1996) to estimate water-renewal time-scales in various basins.

The water age represents the mean age of the water in a grid cell of the numerical model employed for the investigation, and thus this value results from the mixing of water parcels of different ages within each cell. To determine exactly how much of the 'original water' (i.e. that initially present in the model domain) the grid cell contains at a given moment, we can use another auxiliary variable which will be denoted the 'renewal index'. This is defined as a function of location and time and represents the evolution of the amount of original water and can be described mathematically by an advection-diffusion equation. The initial concentration of the renewal index is prescribed as 100% inside the entire modelling domain, and outside the value is set to zero. During the simulation, the original water mass of the basin is gradually replaced by inflows across the open boundaries as well as from rivers, leading to a reduction in the value of the diagnostic quantity. This variable shows how much original water the grid cell contains and can thus be expected to reveal the least ventilated areas of the modelled basin. By integrating this concentration over the model domain (or a part of it), it is possible to estimate the total amount of original water present at given time. When the magnitude of the renewal index in each grid cell decreases below some a priori specified value (in what follows taken to be 2% – the number in principle depending on the task to be solved), the time required for attaining this state is defined as the renewal time of the water in the basin. While the water age provides information concerning the mean age of water in a grid cell, the renewal index shows how much of the original water this cell still contains at a given time. It is worth noting that implementing an e-folding law to estimate the wash-out time-scale of the constituent yields a cruder measure, because the original advection-diffusion equation can only be reduced to an exponential-decay equation under the severe restriction of neglecting the spatial inhomogeneities of the advection-diffusion equation variables.

Both of these diagnostic variables (denoted $A_{1,2}$) are governed by an advection-diffusion equation:

$$\frac{\partial A_{1,2}}{\partial t} + \frac{\partial u A_{1,2}}{\partial x} + \frac{\partial v A_{1,2}}{\partial y} + \frac{\partial w A_{1,2}}{\partial z} = \mu \Delta A_{1,2} + \frac{\partial}{\partial z}\left(\vartheta \frac{\partial A_{1,2}}{\partial z}\right) + F_A. \quad (1)$$

Here, u, v and w are the velocities in the x-, y- and z-direction, respectively. A_1 is the water age and A_2 is the renewal-index concentration, μ and ϑ are the horizontal and vertical kinematic eddy diffusivity coefficients, respectively, and Δ denotes the horizontal Laplacian operator. F_A is a source term, equal to 1 in the water-age equation and 0 in the equation for the renewal index. When this equation is solved numerically, initial as well as boundary conditions must be prescribed. As initial conditions we used $A_1 = 0$ d for the water age and $A_2 = 100\%$ for the renewal index. (The water-age initialization is in fact somewhat arbitrary, because we examine the model results after a 5-yr numerical experiment when essentially all the water in the Gulf of Finland has been exchanged.) At the open boundary towards the Baltic proper as well as at the pointwise freshwater sources on the solid boundaries, A_1 and A_2 were prescribed as 0. At the solid boundaries as well as the free surface of the Gulf, no-flux conditions were assumed to hold.

Both variables are thus controlled by the advection through the grid-cell walls and mixing and they are also affected by the vertical convection.

5. Results of the numerical simulations

The main interest as regards the modelling results is focused on the analysis of the water age and renewal index of the water masses in the Gulf of Finland (see Fig. 1). Some comparisons between observations and model results from the middle of the final month of the model run (August 1992) were made in order to examine the model's capacity of reproducing the main hydrographic features of the Gulf, and have been presented by Andrejev et al. (2003). According to the field measurements, the surface temperature varied between 12 and 18 °C, and the surface salinity ranged from 0 psu in the eastern Gulf up to 6.5 psu at the exit to the Baltic proper. It was concluded that the model does justice to the surface temperature and salinity with an accuracy of around 0.5 °C and 0.5 psu, respectively. A comparison between the predicted and observed sea levels from Helsinki during the period 1 January to 30 April 1992 furthermore showed a good agreement between the phases and amplitudes of the measured and modelled sea levels.

The results from the numerical simulations can be expected to provide us with useful information about the spatio-temporal

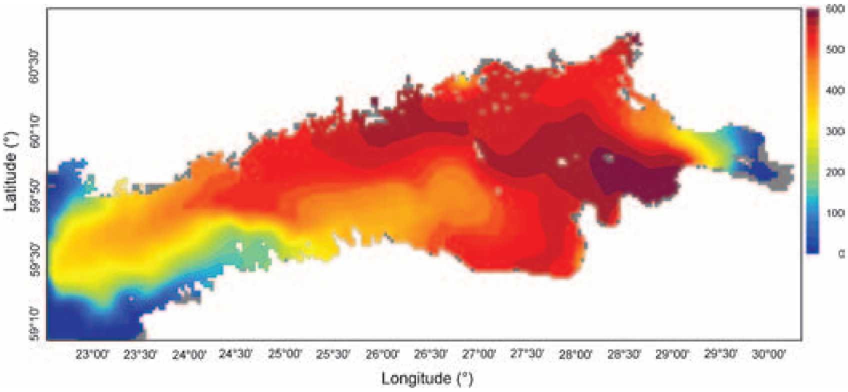

Fig 4. Horizontal distribution of the water age (d) in the near-surface layer between 2.5 and 7.5 m on 31 August 1992.

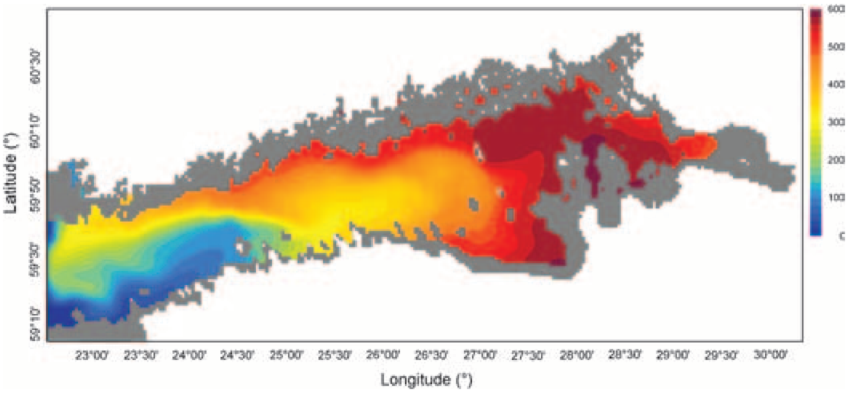

Fig 5. Horizontal distribution of the water age (d) in the subsurface layer between 22.5 and 27.5 m on 31 August 1992.

variability of the water age. It is of considerable interest to examine whether the inflow–outflow system described above, cf. Figs. 2 and 3, is also reflected in the structure of the water age distribution, not least because for practical purposes it would be highly useful to determine a possible upper limit of the water age in the Gulf of Finland. Figure 4 thus represents the water age in a near-surface layer of the model (2.5–7.5 m) after a 5-yr simulation.

The horizontal distribution of the water age shown in Fig. 4 agrees with previously determined results for the circulation and the current persistency (cf. Figs. 2 and 3). Low water ages are thus noticeable at the Estonian coast, along which the Baltic waters enter the Gulf. In the south-western part of the Gulf, the water age varies between 10 and 220 d, whereas it increases up to 450 d in the southern part of the central Gulf. Water ages are also low at the westernmost part of the Finnish coastal zone with values typically between 80 and 250 d, reflecting the weak surface-layer inflow characterizing this region. In the central part of the Gulf, high water ages are found (reaching a maximum of 500–580 d) and in the eastern part of the central Gulf the age can reach 590 d. These high water ages are associated with the internal circulation, in particular the meso-scale eddies and cyclonic circulation cells. In the eastern Gulf, the water age decreases drastically from around 550 d in the Seskar basin to 100 d near the island of Kotlin. The water ages in the easternmost Gulf are between 0 and 100 d, where the role of the freshwater influx from the Neva is clearly visible because the isolines are tilted so that, in general, higher water ages are found on the southern side of the Gulf (consonant with the cyclonic circulation characterizing the uppermost layers of the Gulf).

In the deeper layers (Fig. 5) the water ages in the southern part of the Gulf are lower than at the surface, and an area of comparatively low values from 100 to 300 d extends to 27°E along the southern coast. Although the area of high water ages becomes smaller in the eastern part of the central Gulf, a region with water ages of up to almost 600 d is found here due to the internal circulation. In the lowest layers, i.e. deeper than 45 m, the water ages are very low in the western Gulf due to the inflow, whereas farther to the east higher ages are found.

A vertical section along the Gulf (Fig. 6) shows that the inflow takes place over a rather thick layer, whereas the vertical extent of the outflow is smaller. There is a clear difference between the water ages of the two water masses taking part in this process, because the outflow in the western Gulf has a water age which is 100–250 d higher than that of the corresponding inflow. In the central Gulf, where no pronounced halocline exists, the water age is almost homogeneous with depth, whereas in the easternmost Gulf the vertical gradients of the water age are caused by the Neva outflow. It is also of interest to note that the 'stratification' of the water age at the two ends of the Gulf differs, because in the

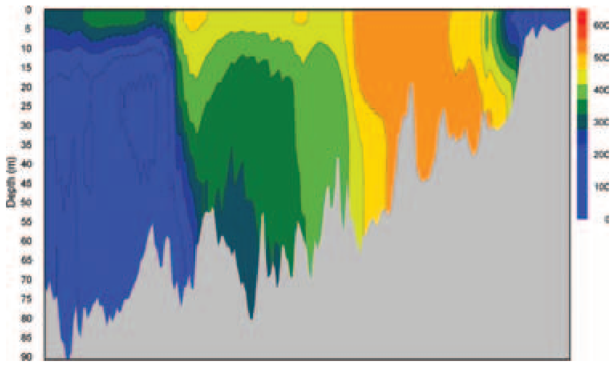

Fig 6. The simulated west–east section of the water ages (d) at the conclusion of the experiment on 31 August 1992 (see location of the section in Fig. 1).

western part water masses with low age extend beneath waters of higher age, whereas in the eastern part of the Gulf the inverted situation holds true.

In order to examine its temporal evolution, the water age also was investigated on the basis of a 3-yr simulation. It was found that the general features of the water-age field were established already after this period and that the maximal water age did not change much hereafter (although note that minor fluctuations of both the horizontal and vertical structure occur continuously).

Figures 7 and 8 pertain to the water age and the renewal index, respectively. The diagrams represent 'snapshots' of the 2.5–7.5 m layer over the eastern part of the Gulf of Finland at the end of August 1988, i.e. after 13 months of the model run. Qualitatively these results are similar, but some differences may be noted. The renewal index has a maximum exceeding 32% in Koporskaya Bay (59°53′N, 28°50′E), in the north-eastern part of which the water age is below 300 d (see Fig. 1). A water-age maximum of more than 330 d is found near the eastern coast of Moshnyj island (60°00′N, 27°54′E). The renewal index here is also high, but smaller than in Koporskaya Bay. Hence the region near the eastern coast of Moshnyj island contains a smaller proportion of original water than does Koporskaya Bay, but the remaining part of the water at this latter location is older. For both regions the mean velocities are very weak (1–2 cm s^{-1}), and thus it could be assumed that Koporskaya Bay should be the most vulnerable area for eutrophication, as indeed confirmed by recent observations (Lyakhin et al., 1997) showing an oxygen deficit under the halocline during the summer of 1996. Even more interesting features are discernible adjacent to the River Neva outflow, where water age increases rather rapidly towards the west despite the fact that the amount of original water is comparatively limited. The mean velocity field shows a complicated velocity pattern in this transition zone between the large-scale cyclonic vortex characterizing the inner Gulf of Finland and the

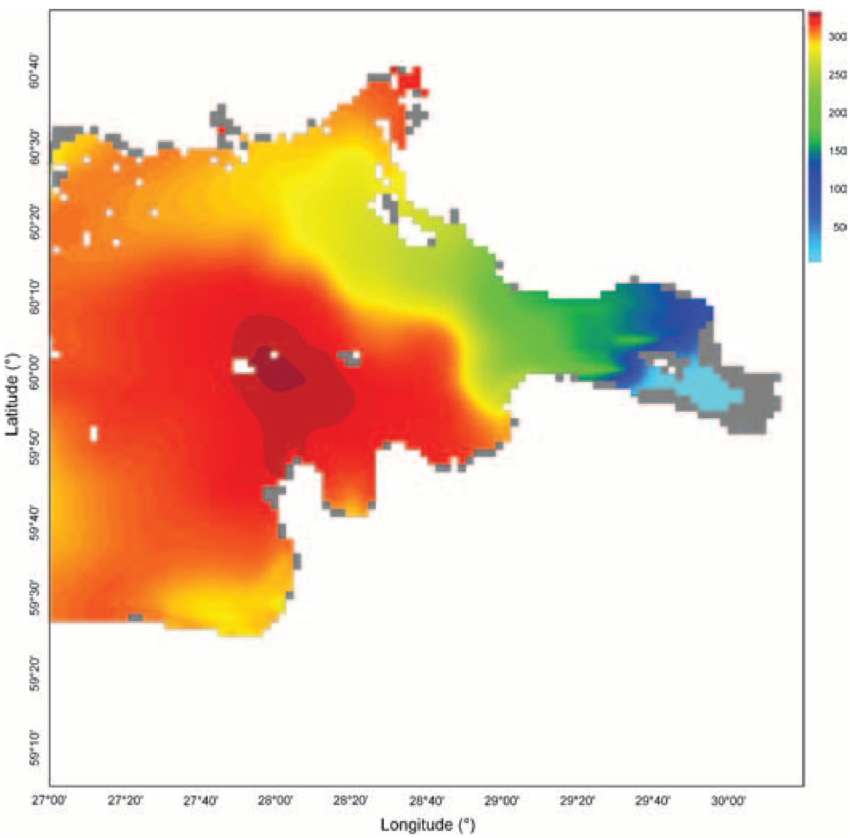

Fig 7. The near-surface (2.5–7.5 m) water age distribution over the eastern part of the Gulf of Finland after 13 months of simulation.

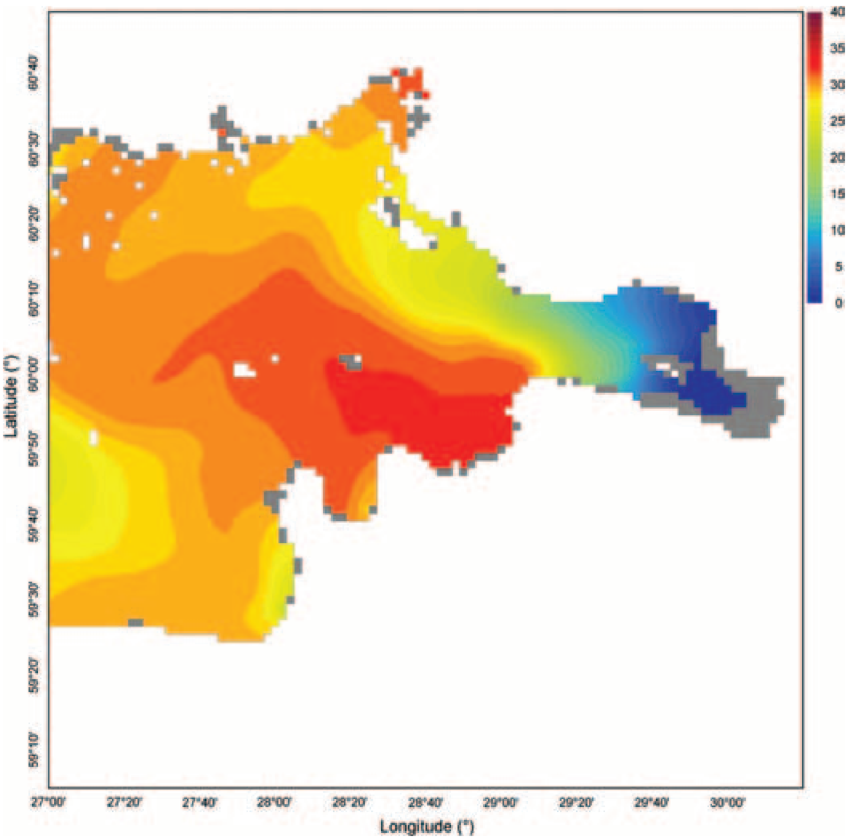

Fig 8. The near-surface (2.5–7.5 m) renewal index distribution over the eastern part of the Gulf of Finland after 13 months of simulation.

circulation induced by the Neva discharge. As a result, vertical motion associated with the closed circulation cells visible in Fig. 9 (with a persistency of up to 50%) acting on new water from the River Neva results in distributions of the auxiliary variables which differ considerably from one another. Similar discrepancies between the distributions of water age and renewal index are found also in other parts of the Gulf, e.g. at the southern coast near Tallinn and in the central basin west of the island of Hogland. Despite the fact that the distributions of these two characteristics tend to resemble each other, there are regions where a simultaneous analysis of the auxiliary variables can provide additional insights concerning water quality.

In Fig. 10 the remaining fraction of the water initially present in the Gulf is shown as the solid curve. This graph demonstrates that an intense renewal takes place during the first four months of the numerical experiment, when almost 40% of the original water masses were replaced by 'new' Baltic and river waters. Approximately 3 yr were required for the replacement level to reach 90%, whereafter the renewal process became more protracted. Hence even after a 5-yr simulation, around 2% of the original water is still present. As a consequence of this asymptotic behaviour, it is difficult to a priori estimate the time required to replace the entire Gulf water. It may also be remarked that the quasi-steady distribution of the water age coincides with the overall state at the time when the water renewal process started to behave asymptotically. The dashed line in Fig. 10 demonstrates the best exponential fit to the model results. It is recognized that the integral of the renewal index behaves as an almost perfect exponential after a simulation of around 2 yr, at which time the Gulf contains only about 20% of the original water and the renewal index at the open boundaries of the Gulf has become small and almost entirely homogeneous. Only under these latter conditions does an ordinary exponential-decay equation for the renewal $R \approx 80.0\mathrm{e}^{-0.0061t}$ provide results more or less in agreement with those from equation (1).

6. Summary and conclusions

Calculating the amounts of inflowing and outflowing water (Knudsen, 1900) only yields rather limited information concerning water-renewal rates in semi-enclosed basins, because these straightforward estimates do not reflect the internal dynamics of the basins. For this purpose, a simultaneous analysis of the complementary variables of water age and renewal index can instead be used to provide information regarding water quality. For each area of the basin, the water age shows the mean age of its water masses, whereas the renewal index yields the amount

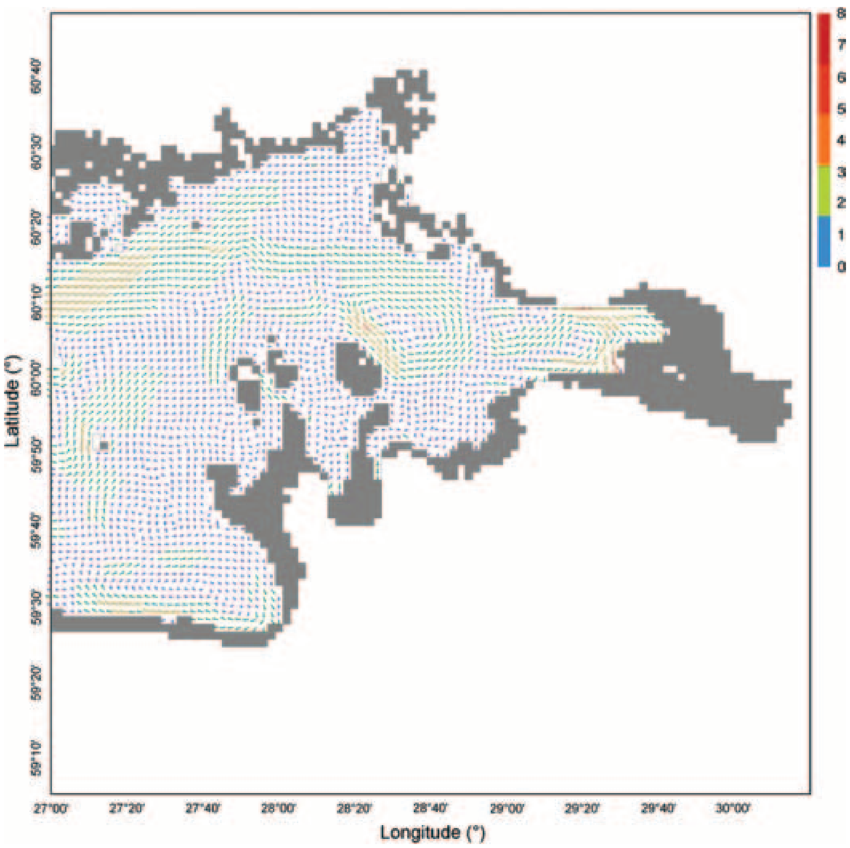

Fig 9. The mean current field in the layer between 12.5 and 17.5 m over the eastern part of the Gulf of Finland.

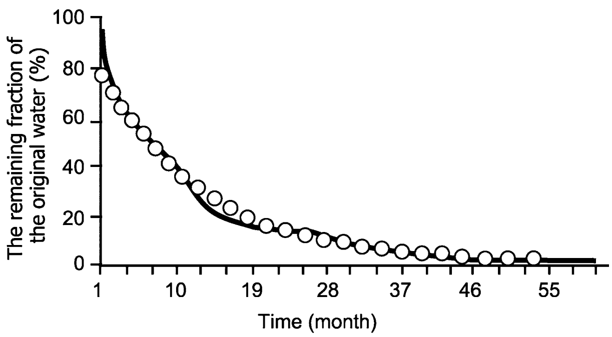

Fig 10. The modelled remaining fraction of the original water in the Gulf of Finland (in per cent) as a function of time. The dashed curve pertains to the best exponential fit.

of new (in an *ab initio* sense) water present at a given time. The local extrema of these two quantities do not always coincide. The areas where local maxima of the renewal index coincide with the presence of water masses characterized by a significant age can thus be regarded as the ecologically most vulnerable regions of the basin.

A 5-yr numerical simulation of the hydrographic conditions and circulation in the Gulf of Finland yielded useful information concerning the water-renewal rate of the Gulf: The age concentration of the water showed a pronounced horizontal variability, with the smallest values being found in inflow regions and at river mouths, whereas the highest water ages were encountered in the outflow regions. This pronounced variability is associated with the internal dynamics of the Gulf, where the overall distribution of the water age is consonant with the notion of a cyclonic mean circulation. A number of eddies, fronts and cyclonic circulation cells appear to be of a quasi-stationary nature because they only show a slight variability in time, and in such areas the water age tends to be significant. The numerical results indicate that the water age in the Gulf is at the most 2 yr. During the winter season, convection becomes important, and the vertical variability of the water age decreases during this period of the year. The highest water ages are found in the south-eastern parts of the Gulf and are reflected in the environmental state of this region. The area of maximal renewal index against a background of significant water age was found in and north of Koporskaya Bay, consonant with recent observational results due to Lyakhin et al. (1997). The regions associated with the highest water ages are the most vulnerable to eutrophication effects, in particular the sedimentation of organic matter, and hence specific focus on the welfare of these areas may be advisable. A practical way to follow the ecological state of such areas could be to establish a new monitoring station in the area.

To conclude this study, it must be emphasized that the renewal-index results for the Gulf of Finland presented here have not attempted to differentiate between the two main sources of the renewal: the Neva discharge and the inflow from the Baltic proper. Because the characteristics of the 'source waters' are of great importance when judging the ecological and/or toxicological effects on the system, in coming work attention will be directed towards resolving this specific problem.

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